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ABSTRACT

The solar magnetic field is twisted into an Archimedes spiral by the outward flowing solar wind; this spiral field must also, on the average, co-rotate with the sun in order for the solar wind to move radially outward without cutting magnetic lines of force. The interaction between the solar wind and the galactic magnetic field and interstellar medium results in the formation of a shock wave at a heliocentric distance of the order of 50 A.U. Beyond the shock the energy of the solar wind is transferred to the inter-

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stellar neutral atomic hydrogen by charge-exchange. Instabilities at the boundary between the solar plasma and the galactic medium cause blobs of solar plasma to form which are disconnected from the solar magnetic field by Sweet's mechanism; oppositely-directed lines of force are joined to make large semi-permanent magnetic "tongues." The solar wind energy that is transferred to neutral hydrogen is transported out into the galaxy by radiation or thermal conduction. It is found that the solar magnetic field does not permit solar wind velocities less than about 100 km/sec.

I. INTRODUCTION

This paper is devoted to an examination of some of the effects of the expanding solar corona (hereafter referred to as the solar wind) on the sun's magnetic field (which constitutes the interplanetary magnetic field) and of the boundary conditions in the region where the solar wind and interplanetary magnetic field interact with the galactic magnetic field and interstellar material.

The thermal structure of the solar atmosphere requires that the corona be continuously heated. Heat is conducted downward from the 10^6 °K corona toward the 6×10^3 °K photosphere; also, thermal energy is carried away by the solar wind. Chamberlain (1961) and Parker (1960) have shown that, as a direct consequence of supplying heat to maintain the corona at its observed temperature, the corona must expand continuously if the solar magnetic field is disregarded. (It will be argued later that the neglect of the solar magnetic field is not justified for small solar wind velocities.) The velocity of expansion is approximately proportional to the square root of the total heat input. Chamberlain assumes that the corona is heated only ir a thin layer near the base of the corona while

Parker assumes that the heat input extends from the base of the corona out to about 8 solar radii. From these dissimilar boundary conditions, solar wind velocities of about 20 km/sec and 500 km/sec are derived.

The various pertinent satellite and space probe data are not yet sufficiently unambiguous or reproducible to allow definite conclusions to be drawn regarding the solar wind and interplanetary magnetic field. However, in our opinion, the data favors the high velocity solution. Therefore, in this paper, we assume solar wind velocities of the order of several hundred km/sec.

II. THE SPIRAL STRUCTURE OF THE INTERPLANETARY MAGNETIC FIELD AND ITS CO-ROTATION WITH THE SUN

Due to the rotation of the sun about a spin axis, a stream of material directed radially out from the sun, follows the form of an Archimedes spiral--the "garden-hose effect" (Chapman and Bartels 1940). Parker (1958, 1962) has shown that if this result is extended to a uniformly expanding corona and if the concept of "frozen-in flux" is applied to the solar magnetic field, a spiral inter-planetary magnetic field structure is produced, provided that the kinetic energy density of the solar wind is much larger than that of the magnetic field. A magnetic line of force follows the form of an Archimedes spiral. For distances beyond about 0.1 A.U., the radius of the sun may be neglected and the form of the spiral is written as,

$$r = (V_s/\Omega)\ (\phi - \phi_o)$$

where V_s is the solar wind velocity, Ω is the angular velocity of the sun, and ϕ is the heliocentric longitude measured from a reference longitude ϕ_o.

The magnetic field strength in the solar equatorial plane (after Parker 1958) is given by,

$$B_t = B_o\ (a/r)^2 \quad (1 + \Omega^2 r^2/V_s{}^2)^{1/2} \qquad (1)$$

$$B_{\parallel} = B_o\ (a/r)^2 \qquad (2)$$

$$B_{\perp} = B_o\ a^2\Omega/(rV_s) \qquad (3)$$

where B_t is the total magnetic field strength at a distance r from the sun, B_o is the field strength at the photosphere, a is the radius of the sun, $B_{\parallel}$ is the component of B_t parallel to the radius vector and $B_{\perp}$ is the component perpendicular. From (1) we see that for small r, B_t varies as $1/r^2$ while for large r, B_t varies as $1/r$. In Figure 1,

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$B_{\parallel}$ and $B_{\perp}$ are given as functions of r for B_0 = 1 gauss; $B_{\perp}$ is shown for 3 values of V_s. B_t is shown in Figure 2 for 3 values of V_s over a limited range of r near 1 A.U. (The value for Ω corresponds to an equatorial rotation period of 24.7 days rather than apparent or synodic 27 days period; obviously the motion of the earth about the sun does not affect the strength of the interplanetary field.) Note that over the chosen range of V_s and r, the magnetic field strength is a rather sensitive function of V_s; for solar wind velocities less than about 300 km/sec, the field strength is significantly greater than given by the $1/r^2$ approximation.

Above or below the equatorial plane, the field lines are in the form of helices that spiral out along conical surfaces. The vertex angle of a given cone should be roughly the polar angle of the associated field line at the surface of the sun. The field lines emerging near the sun's polar axis are spiraled in essentially a corkscrew pattern.

The ratio (β) of the solar wind kinetic energy density to the magnetic field energy density is approximately constant for large r since both $B_t{}^2$ and $\frac{1}{2}nmV_s{}^2$ vary as $1/r^2$, n being the proton number density in the solar wind and m the proton mass. For small r and large V_s, β varies about as r^2. Thus if β is large at, say 1 A.U., then it is also large at greater distances.

The solar wind cannot expand if $\beta < 1$. At 1 A.U., taking the solar wind density to be 10 electron-proton pairs/cm^3 and B_t from Figure 2, we find that $\beta \sim 2$, 10^2, 3×10^3 when $V_s = 100$, 300, and 1000 km/sec respectively. At 0.1 A.U., $\beta = 1/2$, for $V_s = 100$ km/sec, the solar wind mass density increased by the $1/r^2$ factor, $1/(0.1)^2 = 100$, to $10^3/cm^3$, and $B_o = 1$ gauss. At about 0.1 A.U. and beyond, and for velocities smaller than about 100 km/sec, β is proportional to $V_s{}^4$, inversely proportional to $B_o{}^2$, and directly proportional to the solar wind mass density. Thus it appears that the solar magnetic field does not permit solar wind velocities smaller than about 100 km/sec. That is, unless some very special magnetic configuration is assumed, the solar wind velocity either is greater than $\sim$ 100 km/sec or is zero. This conclusion is consistent with the interpretation of cosmic ray diurnal variation observations between 1937 and 1959 (Ahluwalia and Dessler 1962) that indicated that the solar wind velocity seldom, if ever, fell below 100 km/sec during the 23-year period. Therefore we will restrict our attention to solar wind velocities greater than 100 km/sec.

Inspection of solar magnetograms (Babcock and Babcock 1955) show that the sun's magnetic field at the photosphere may be separated into regions of north and regions of south magnetic polarity having field strengths of the order of 1 gauss; in addition, there appears to be a general dipole field. The size of a region of one magnetic polarity varies between about 10^{-2} and one-half the area of the solar disc. The general field of the sun may be thought of as divided into tubes of flux, some tubes containing field lines leaving the sun while other tubes contain field lines returning to the sun so that the net flux leaving the sun is zero. We suggest that the oppositely directed magnetic field lines are mostly joined far beyond the earth's orbit in a region where merging by Sweet's mechanism becomes possible. (Recombination of electrons and protons does not seem to be important due to the low densities that are prevalent at these and even shorter heliocentric distances.) The looped field lines so produced may be regarded as semi-permanent magnetic tongues. Smaller more transient magnetic tongues may develop from time to time without essentially altering this model.

Far from the sun, where $B_\perp >> B_\parallel$, the paths of the magnetic field lines in the equatorial plane are nearly circular, that is, the increase in r in one revolution is small compared to r. The radial thickness of a tube of flux of one sign is

$$d = \Delta\phi \; V_S/\Omega \qquad (4)$$

where $\Delta\phi$ is the angular extent of a region at the solar surface of one magnetic polarity. A typical value for $\Delta\phi$ might be 30°, which yields $d \sim 0.3$ A.U. for $V_S = 300$ km/sec. Thus, in this region we expect to find that in a radial traverse, the interplanetary field reverses its direction every few tenths of an A.U. The highly conducting solar plasma tends to prevent the oppositely directed field lines from moving together and cancelling each other.

The conditions, (1) a spiral magnetic field and (2) a highly conducting plasma moving radially outwards, are satisfied by the co-rotation of the sun with the spiral interplanetary field (Ahluwalia and Dessler 1962). The resolution of velocities is shown in Figure 3. An instructive analogy can be made with a needle on a phonograph record--

the needle moves (nearly) radially at a constant velocity while the spiral groove rotates as a rigid body. The important feature of the analogy is that the plasma is free to slide along (but not across) the magnetic field lines just as the phonograph needle is free to slide along (but not across) the record groove.

It should be noted that the toroidal magnetic field produced at great distances from the sun does not exert any torque on the sun or the inner part of the corona; no influence can be propagated back towards the sun from beyond the radial distance at which the solar wind becomes supersonic. Using Parker's estimates (1962) of V_s as a function of r, we find that the escaping solar gas can be forced to co-rotate with the sun only within about 10 solar radii. If we fix the solar wind angular momentum at 10 solar radii, the rotational velocity of the solar plasma at 1 A.U. is about 1 km/sec--a negligible velocity compared to the minimum solar wind velocity.

III. LIMIT OF CO-ROTATION OF THE INTERPLANETARY-MAGNETIC FIELD

The solar wind continues to flow radially outward until stopped by external forces. Two possible forces are apparent: (1) As pointed out by Davis (1955), the dynamic pressure of the solar wind, which falls off as $1/r^2$, can be balanced at some heliocentric distance by the galactic magnetic field. (2) The solar system is embedded in galactic neutral hydrogen atoms; solar wind protons moving through the neutral hydrogen will suffer charge-exchange collisions and stop in a relatively short distance. Other forces, such as cosmic ray pressure gradients, do not appear to be significant (e.g., Parker 1962, Chapter 9).

(a) The Interplanetary Shock Transition

These external forces cause the supersonic solar wind to undergo a shock transition to a subsonic condition at some heliocentric distance, S (of the order of 50 A.U.), as indicated in Figure 4 (Clauser 1960; Weyman 1960). This transition is analogous to that occurring in the supersonic section of a Laval nozzle when the pressure locally becomes less than the exit pressure (e.g., Saunders 1956, pp. 202-5).

Since the hydromagnetic Mach number (M) of the solar wind is likely to be rather large ($M \gtrsim 10$ beyond 1 A.U.), the shock transition will be "strong" in the aerodynamic sense (Courant and Friedrichs 1948, pp. 154-5). Thus, if the ratio of specific heats is taken to be 5/3 then

$$n_2/n_1 = V_{s1}/V_{s2} = B_2/B_1 \sim 4 \qquad (5)$$

where the subscript 1 refers to conditions upstream of the shock, and 2 downstream. The radial component of the magnetic field is unchanged by the transition. The pressure behind the shock is

$$P_2 \sim \frac{3}{4} \ (n_E m V_{sE}^2/S^2), \qquad (6)$$

where n_E and V_{sE} are the solar wind density and velocity respectively at 1 A.U. (It is assumed that V_s is effectively constant and equal to V_{sE} between 1 A.U. and S A.U., and that the density decreases inversely as the square of the heliocentric distance.) The mean of the electron and proton temperatures corresponding to this pressure is approximately

$$T_2 \sim S^2 p_2/(8n_E k) \sim \frac{3}{8} \ mV_{sE}^2/k,$$

where k is Boltzmann's constant. For V_{sE} = 300 km/sec, $T_2 \sim 4 \times 10^6$ °K, which is somewhat larger than the corresponding coronal temperature (Parker 1960); the higher temperature is due to the heat that is added to the solar gas after it is flowing away from the sun.

(b) The Charge-Exchange Process

Charge-exchange between solar protons and neutral hydrogen atoms may be the most important factor in the interaction between the solar wind and the interstellar medium. This process (which should take place in the compressed region beyond the interplanetary shock transition) depends for its effectiveness on the existence of a suitable inflow of neutral hydrogen towards the sun. We shall assume for the purposes of discussion that this inflow is sufficient to remove a proton flux of about $10^8/cm^2$-sec^1 at 1 A.U., and that the neutral hydrogen density is of the order of $1/cm^3$ (e.g., Oort, Kerr, and Westerhout 1958). This assumption is discussed at greater length in Section IV.

For hydrogen-proton charge-exchange, the reaction rate (the product of cross section and relative velocity) differs from it average value by less than a factor of two between about 2×10^2 and 3×10^3 km/sec relative velocity (Fite, Stebbings, Hummer, and Brackmann 1960; also see Figure 2 of Dessler, Hanson, and Parker 1961). The average value for the reaction rate R is 1×10^{-7} cm^3/sec. In an element of volume where the number density of neutral hydrogen is n_H, the time constant for the charge-exchange process is

$$\tau = 1/(Rn_H). \tag{8}$$

The disordered velocities of protons in the compressed region just beyond the interplanetary shock transition are of the order of V_{SE}. When a charge-exchange event occurs between such a proton and an interstellar hydrogen atom, the former accepts an electron and becomes a high velocity hydrogen atom moving in a straight-line path unaffected by the magnetic field, while a proton of relatively low energy is left behind. If this hydrogen atom (travelling at several hundred km/sec) moves back towards the sun it will continue to undergo charge-exchange collisions until it is driven out again. Thus the net effect is for protons in the compressed region to lose most of their energy with the accompanying ejection of a shower of energetic hydrogen atoms in the general direction away from the sun.

The collision mean free path of these hydrogen atoms is of the order of 100 A.U. in the galactic hydrogen (if $n_H = 1/cm^3$). The energetic hydrogen atoms transfer their energy to the galactic hydrogen within a few hundred A.U. of the sun; this energy can be carried away into the galaxy by radiation or thermal conduction.

The temperature of the solar plasma in the boundary shell (region II) should tend to be reduced by charge-exchange collisions to the temperature of the neutral galactic hydrogen. The thermal relaxation time through proton-proton collisions is long compared with the charge-exchange time; in fact, under the conditions expected for the compressed region, the time required for collisional energy exchange between kilovolt energy protons (Spitzer 1956) is of the order of 10^{11} seconds, while $\tau \sim 10^{7}$ seconds for $n_H = 1/cm^3$--thus the charge-exchange cooling is comparatively efficient.

(c) The Boundary Shell

It can be assumed that the total pressure is approximately constant throughout the compressed boundary shell (region II in Figure 4) that separates the galactic magnetic field from the region of supersonic solar wind (I); assumption is justified because $M << 1$ in II. Just beyond the shock wave, the flow can be regarded as being incompressible with T and n roughly constant. Thus $V_s \sim S^2 V_{s1}/4r^2$, r being measured in A.U., and from (1) and (3):

$$B_t \sim B = 4B_0 a^2 \Omega r / S^2 V_{s1}, \text{ for } r > S, \qquad (9)$$

so that the magnetic field winds up at a rate that tends to increase in direct proportion to the distance from the sun. The solar magnetic field cannot be strengthened indefinitely in this way however, since $B_t^2/(8\pi)$ cannot exceed the total inwards pressure exerted by the galactic magnetic field and the interstellar medium (region III). When $B_t^2/(8\pi)$ approaches this limiting value, the magnetic field takes control of the outflowing gas and the gas is forced to expand in such a manner that B_t does not become too large. If charge-exchange becomes important, then B_t increases more rapidly than indicated by (9) because the local plasma pressure is reduced to the temperature of the neutral galactic hydrogen. In either case, (9) becomes invalid beyond the point at which the magnetic pressure exceeds the plasma pressure.

At some sufficiently great distance (S* A.U.) there must be a boundary (perhaps diffuse) that separates the solar from the galactic magnetic field, as indicated in Figure 4. Within this boundary the solar magnetic field closes on itself to form semi-permanent magnetic tongues, although transient connections with the galactic field may also occur. In the latter case solar gas can move directly onto the galactic magnetic field lines. Otherwise blobs carrying magnetic fields become detached and move out into region III where they gradually diffuse away. (The processes that permit the plasma to slip through into region

III and solar magnetic field lines to merge are discussed in the following sub-section.) In this manner an equilibrium situation can exist in which the solar plasma moves radially out into the interstellar medium while the solar magnetic field co-rotates with the sun in region I without any contradiction arising.

It should be noted that within region II, there are 6 distinct components in proportions that vary with radial distance and time: (i) a magnetic field of solar origin, (ii) cold neutral atomic hydrogen falling towards the sun from the interstellar medium, (iii) high energy protons with random velocities of the order of V_s, (iv) low energy protons resulting from charge-exchange with interstellar hydrogen, (v) high energy neutral hydrogen atoms moving at speed comparable to V_s, also resulting from charge-exchange, (vi) low energy electrons. Outside the boundary shell the interstellar medium consists of a magnetic field and neutral atomic hydrogen--a plasma component is also present, but since its density and pressure are probably small, it may be disregarded. Cosmic rays are present in both regions, but these do not contribute to the dynamics because their energy densities in regions II and III are essentially equal (Parker 1962).

(d) Detachment of Plasma from the Solar Magnetic Field

Some dissipative process that allows solar plasma to slip through the solar magnetic field and be removed from the solar magnetic field must be present if the boundary shell (region II) is not to grow indefinitely with time. Charge-exchange only replaces an energetic proton with a slow one; that is, during the charge-exchange process no charged particles cross the interface between regions II and III. Radiative recombination of protons and electrons does not provide a means of allowing the solar plasma to slip away from the solar magnetic field since the process is very slow; the recombination time is $\sim 3 \times 10^9\ T^{3/4}/n$ (Allen 1955, p. 89), i.e., of the order of thousands of years even with excessively favorable values of T and n.

Instabilities of one sort or another are likely to be most significant in permitting blobs of solar plasma (with associated magnetic field) to form and move away into interstellar space as indicated in Figure 4. The magnetic connection between region II and III is probably broken by magnetic merging through Sweet's mechanism. Since the interface between regions II and III is concave towards the solar plasma it should be subject to interchange instabilities, as pointed out by Davis (1962). Rayleigh-Taylor instability (e.g., Chandrasekhar 1961) may also occur when the solar wind stagnation pressure changes and hence causes some acceleration of the interface between regions II and III. If this acceleration is inwards (i.e., during a period of decreasing solar wind intensity) the surface is unstable since this is a case of acceleration of a light fluid toward a heavier fluid.

Whatever the actual instability mechanism may be, in the volume where the escaping blob is to be detached from region II, two regions of oppositely directed field lines must be merged. This merging may be most effectively accomplished by Sweet's mechanism. The merging time by Sweet's mechanism (see Parker 1957) is

$$t_m = L^{3/2}\ \sigma_3^{1/2}/(V_{hm}\ c)$$

where V_{hm} is the hydromagnetic wave velocity, σ_3 is the electrical conductivity, see Cowling 1956), c the velocity of light, and L is the width of the region over which merging takes place. The particle densities and magnetic field strength are not known well enough to make a meaningful calculation of t_m; however, we can make a simple calculation that suggests that the merging time will be of the order of the proton-hydrogen charge exchange time.

Let us assume the following conditions for the outer part of the boundary shell: 1 neutral hydrogen atom/cm^3, 0.1 proton and electron/cm^3, $B = 10^{-5}$ gauss, an electron temperature of 10^4 $^\circ$K, and an ion-atom collision period equal to the charge-exchange period of 10^7 seconds. We can calculate σ_3 using the standard electrical conductivity formulas (e.g., Hanson 1961). If we assume a quasistatic merging time long compared to the collision frequencies and solve for the dc conductivity, a value for σ_3 of 10^7 statmho/cm is obtained; the corresponding value for t_m is 10^9 sec if L is 1 A.U. and 3×10^7 sec if $L = 0.1$ A.U. Therefore, we may expect the merging of the magnetic fields in the above case to be several times the ion-atom collision time, which is the charge-exchange time (Dessler 1959), i.e., t_m should be $\sim 10^8$ sec or about 3 years.

The 3-year merging time implies that the boundary shell contains approximately a 3-year supply of solar plasma; i.e., for steady state conditions, the residence time for plasma in the boundary shell must be of the order of the time required to sever the plasma from the solar magnetic field. The boundary shell need be less than 10 A.U. thick to accomodate a 3-year supply of solar plasma if it is compressed to a density between 10^{-2} and $10^{-1}/cm^3$, as described in section III(c).

(e) The Heliocentric Distance to the Interplanetary Shock Transition

If it is assumed that the galactic magnetic field is of primary importance in determining the position of the interplanetary shock transition, then a first approximation to the value of S can be obtained by equating the dynamic pressure of the solar wind to the magnetic pressure exerted by the galactic magnetic field (B_g):

thus

$$n_E m V_{sE}^2/S^2 \approx B_g^2/8\pi$$

or

$$S \approx (V_{sE}/B_g)\,(8\pi n_E m)^{1/2}. \qquad (11)$$

The value of B_g is modified by the distortion of the galactic magnetic field by the solar wind, however, the deviation from the field value at infinity are less than a factor of 2 for any reasonably spheroidal shape. The numberical values of the terms in (11) are not known sufficiently well to establish S within an order of magnitude, but to obtain a working value we provisionally adopt the following: V_{sE} = 300 km/sec, n_E = 10 protons/cm^3,

$B_g = 10^{-5}$ gauss, and so $S \approx 60$ A.U. It should be noted that S could be as small as 5 A.U. (e.g., if $V_{sE} = 200$ km/sec, $n_E = 3$ proton/cm^3, $B_g = 4 \times 10^{-5}$ gauss, or as great as 600 A.U. (e.g., if $V_{sE} = 1000$ km/sec, $n_E = 20$ protons/cm, and $B_g = 5 \times 10^{-6}$ gauss). However, the effects of charge-exchange and perhaps recombination make distances larger than about 100 A.U. unlikely. Of course, the galactic magnetic field does not exert a uniform pressure everywhere, nor is the solar wind likely to be spherically symmetric; thus the cavity (region I) (see Fig. 4) in which the solar wind is supersonic, cannot be expected to be spherical.

IV. DYNAMICS OF THE INTERSTELLAR NEUTRAL HYDROGEN

(a) Neutral Hydrogen Near the Sun

In view of the likely importance of the charge-exchange process in terminating the solar magnetic field, it is of some interest to know whether or not the flux of interstellar hydrogen atoms towards the sun can be comparable with the solar wind flux. Although solar gravitation is an effective means of attracting interstellar hydrogen atoms towards the sun and thereby replacing atoms which have undergone charge-exchange, many of these atoms are lost due to photoionization by solar electromagnetic radiation. Also the inwards flux of neutral atoms is practically constant if gravity alone is effective, so that even if this flux can cope with a typical flux of solar wind protons ($n_E V_{sE} \sim 10^8$ cm^{-2} sec^{-1}), one would expect charge-exchange to have little effect during sustained active periods ($n_E V_{sE} \gtrsim 10^9$ cm^{-2} sec^{-1}) and to overwhelm the solar wind during sustained very inactive periods ($n_E V_{sE} \lesssim 10^7$ cm^{-2} sec^{-1}).

At great distances from the sun, the interstellar hdyrogen atoms are at a temperature of the order of 100 ^{0}K and have corresponding thermal velocities of about 1.6 km/sec. Closer to the sun the atoms gain energy by falling in the solar gravitational field, and their inwards radial velocity is

$$V_H = 42/r^{1/2} \text{ km/sec}, \tag{12}$$

at a heliocentric distance r A.U., provided the mean free path is sufficiently long for collisions to be unimportant. It is possible that the relative velocity between the interstellar gas and the solar system is comparable to that given by (12)--in this case the problem becomes more complex, but the fundamental processes described here are still valid and effective. [The interstellar gas in our neighborhood appears to be moving out from the center of the galaxy with speeds of the order of 6 km/sec (McGee and Murray 1961), and the speed of the solar system relative to early type stars is about 18 km/sec (Allen 1955).]

The number of photons in the Lyman continuum emitted per second by a black body of radius a and temperature T is

$$4\pi \, a^2 \, J \sim \frac{8\pi^2 a^2}{c^2} \left(\frac{kT}{h}\right) \quad (\theta^2 + 2\theta + 2)e^{-\theta} \qquad (13)$$

where h is Planck's constant, $\theta = X_L/kT$ and $X_L = 13.6$ eV is the energy of ionization from the ground state of the hydrogen atom (Kahn 1954). The effective black-body temperature of the sun in the Lyman continuum is 7000 $^{\circ}$K; thus $4\pi \, a^2 J \approx 10^{38}$ photons/sec, which is equivalent to 4×10^{10} photons/cm^2-sec at 1 A.U. The ionizing radiation removes about as many hydrogen atoms by photo-ionization as the solar wind would remove by charge-exchange during a period of very high activity.

There seems to be no difficulty in maintaining an adequate neutral hydrogen density in the charge-exchange region since the absorption of ionizing radiation takes place over relatively long distances and the lifetime of individual hydrogen atoms is also long. The absorption distance (e.g., Goldsworthy 1961, pp. 279-280) is of the order of $1/(\alpha n_H)$ where the absorption coefficient, α, has the value $6 \times 10^{-18}/cm^2$ at the Lyman limit; with $n_H = 1/cm^3$ the radiation is extinguished only at distances of 10^4 A.U. or more. The lifetime against photoionization of a hydrogen atom at a heliocentric distance r A.U., is of the order of $1/(\alpha J) \approx r^2/4 \times 10^{10}\alpha \approx 10^{10}$sec if $r \approx 50$ A.U. Thus a neutral hydrogen atom falling towards the sun from a great distance with an average speed of a few km/sec can move a distance of the order of several hundreds of A.U. without undergoing photoionization, and so may be able to take part in the charge-exchange process we have described. However it is not obvious what the magnitude of the steady inwards flux of neutral hydrogen might be without performing the appropriate detailed calculations.

Photoionization may provide the modulation of the neutral hydrogen flux required to make charge-exchange important for varying solar wind flux densities. The neutral hydrogen loss rate at a given location due to photoionization varies as r^2, since it is proportional to the photon flux. Hence when the solar wind flux density is large, S is large, and photoionization is less effective in removing hydrogen atoms. At the other extreme when the solar wind flux and S are small, the loss due to photoionization of the remaining hydrogen atoms is rapid due to the higher photon flux density.

The neutral hydrogen density near the sun could possibly build up to such large values ($n_H \gtrsim (10^3)/cm^3$) due to gravitational attraction, that the ionizing photons are absorbed in a relatively thin region, the inner edge of which is determined by the solar wind. If this is the case, some of our arguments break down since the hydrogen collision-mean-free-path becomes so small that a continuum treatment is required. The "weight" of the neutral gas could then conceivably be more important than the galactic magnetic field in determining the position of the interplanetary shock transition, and perhaps reduces S to 10 A.U. or even less. However the importance of charge-exchange in stopping the solar wind and allowing the solar magnetic field lines to merge, would not be affected.

(b) Transient Effects

One might think that transient changes in the solar wind velocity and density would simply result in corresponding transient changes in S and S* (see Sections III(d), (e)). However, the solar plasma normally present in regions II and III is sufficiently massive to smooth out most transient fluctuations in solar wind flux.

Suppose, for example, that in quiet conditions $S = 60$ A.U., and $S^* = 70$ A.U., corresponding to $V_{sE} = 300$ km/sec, $n_E = 10/cm^3$, and $B_g = 10^{-5}$ gauss, and that a geomagnetic storm occurs such that the solar wind flux increases to $10^{10}/cm^2\text{-}sec^1$ for 1 day. On the basis of the above figures the total number of protons ejected is $10^{15}/cm^2$ at 1 A.U. These protons will first run into the quiet-day interplanetary medium (region I) as described by Parker (1961) to form an interplanetary shock wave. Since, at 300 km/sec, there is a 1-year supply of solar plasma between 1 and 60 A.U., the enhanced solar wind will run into somewhat greater mass of solar plasma. (In 1 year, $\sim 10^{16}$ protons flow through a 1-cm^2 surface at 1 A.U.). In addition, there is about a 3-year supply of solar plasma in the boundary shell (region II). Therefore, the enhanced solar wind flow of $10^{15}/cm^2$ (at 1 A.U.) will run into the $\sim 4 \times 10^{16}$ protons/cm^2 (at 1 A.U.) that are normally present between 1 and S^* A.U. The storm therefore should result in nothing more than a slight dent in the steady-state configuration, which is restored as more neutral hydrogen atoms fall inwards.

The interplanetary shock transition is likely to be beyond the orbit of Jupiter (i.e., $S > 5$ A.U. at least during periods of moderate and high solar wind activity.) The interstellar hydrogen atom density would have to be rather large of S is smaller than 5 A.U. (or the galactic magnetic field would have to be much larger than commonly believed); if this were true, the values of S and S* would be scarcely affected by short-term increases of solar wind flux. Thus Jupiter would be effectively shielded against magnetic storm effects if S were less than 5 A.U., and this does not appear to be the case (e.g., Carr et al 1961). The variations in the magnitude of comet Schwassmann-Wachmann, which appear to be correlated with solar activity (e.g., Richter 1949), also suggest that S is usually greater than 5 A.U.

We find it difficult to agree with the value $S \sim 2$ A.U. suggested by Brandt and Michie (1962) if the galactic magnetic field alone is effective in producing the transition. We also note that the values $V_{sE} = 300$ km/sec, $n_E = 2$ cm^{-3}, $B_g = 3 \times 10^{-5}$ gauss quoted by these authors, would place the interplanetary shock transition at 25 A.U. according to (11).

At times of very low solar wind flux, it is conceivable that the solar wind is completely overwhelmed by the inwards pressure of the interstellar gas, as well as by magnetic effects. Solar accretion could then take place (Bondi 1952; Mestel 1954), except perhaps near the plane of rotation of the sun where 'slinging' would cause the loss of some solar material as suggested by eclipse photographs taken near sunspot minimum (Gold 1958).

V. CONCLUSIONS

A continuously expanding solar corona leads to a spiral structure for the solar magnetic field (the interplanetary field) that must, on the average, co-rotate with the sun. Because a low expanion velocity (i.e., low solar wind velocity) leads to a tightly wound spiral field and hence a relatively strong interplanetary field, it is argued that the presence of a solar magnetic field, of the order of 1 gauss at the sun's surface, prevents the solar wind from blowing at velocities below about 100 km/sec--that is, if the solar wind velocity is not greater than $\sim$ 100 km/sec, it is zero.

The twofold problem of how the solar wind interacts with the galactic medium, and how the highly conducting solar plasma is eventually disconnected from the co-rotating solar magnetic field is discussed at length. Briefly, the following physical model was derived: At some heliocentric distance ($\sim$ 50 A.U.) the solar wind will undergo a shock transition from supersonic to subsonic flow because of the inward pressure of the galactic medium. Within the supersonci region (region I of Fig. 4), the solar magnetic field, on the average, co-rotates with the sun. Beyond the shock transition, the solar plasma and imbedded magnetic field form a boundary shell (region II in Fig. 4). Within this region, charge-exchange between galactic atomic hydrogen and solar wind protons transfers the solar wind energy to outflowing neutral atomic hydrogen. Also, the charge-exchange process reduces the electrical conductivity by lowering the plasma temperature and by increasing the collision frequencies so that oppositely directed magnetic fields can be merged by Sweet's mechanism in times crudely estimated to be of the order of 3 years. Semi-permanent "magnetic tongues" are thereby formed in the solar magnetic field. Instabilities at the boundary between the solar medium and the galactic medium (the boundary between regions II and III in Fig. 4) allow solar plasma to break away into region III; the magnetic connection between the plasma bubble and the boundary shell is broken by Sweet's mechanism so that blobs of solar plasma drift away into the galactic medium where, through diffusion and recombination, they disappear.

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CAPTIONS

Fig. 1 Values of the interplanetary magnetic field components parallel to the radius vector from the sun ($B_{\parallel}$), and perpendicular to the radius vector ($B_{\perp}$), according to equations (2) and (3). $B_{\perp}$ is shown for solar wind speeds of 100, 300, and 1000 km/sec.

Fig. 2 The variation of the total interplanetary magnetic field strength (B_t) with heliocentric distance for solar wind speeds of 100, 300, and 1000 km/sec. The field strength for solar wind velocities greater than 1000 km/sec is essentially the same as the 1000 km/sec curve. The range of distance is roughly that from the orbit of Venus to the orbit of Mars.

Fig. 3 Vector diagram showing how solar magnetic field lines rotate bodily with the sun while, at the same time, the solar wind moves radially away from the sun. V_s is the solar wind speed, Ω is the angular velocity of the sun, and r is the radius vector.

Fig. 4 A sketch of the proposed cavity produced by the solar wind interacting with the galactic magnetic field. For region I the solar wind is supersonic, and the solar magnetic field lines form Archimedes spirals that co-rotate with the sun. A shock wave occurs at a heliocentric distance S. Beyond this, in region II (the boundary shell), charge-exchange between solar wind protons and interstellar neutral hydrogen takes place and dissipative effects permit oppositely-directed solar magnetic field lines to merge and form closed loops. S* is the distance to the boundary between the solar magnetic field and the galactic magnetic field. Blobs of solar plasma and magnetic field become detached from region II and move out into region III (galactic space) where they gradually diffuse away.

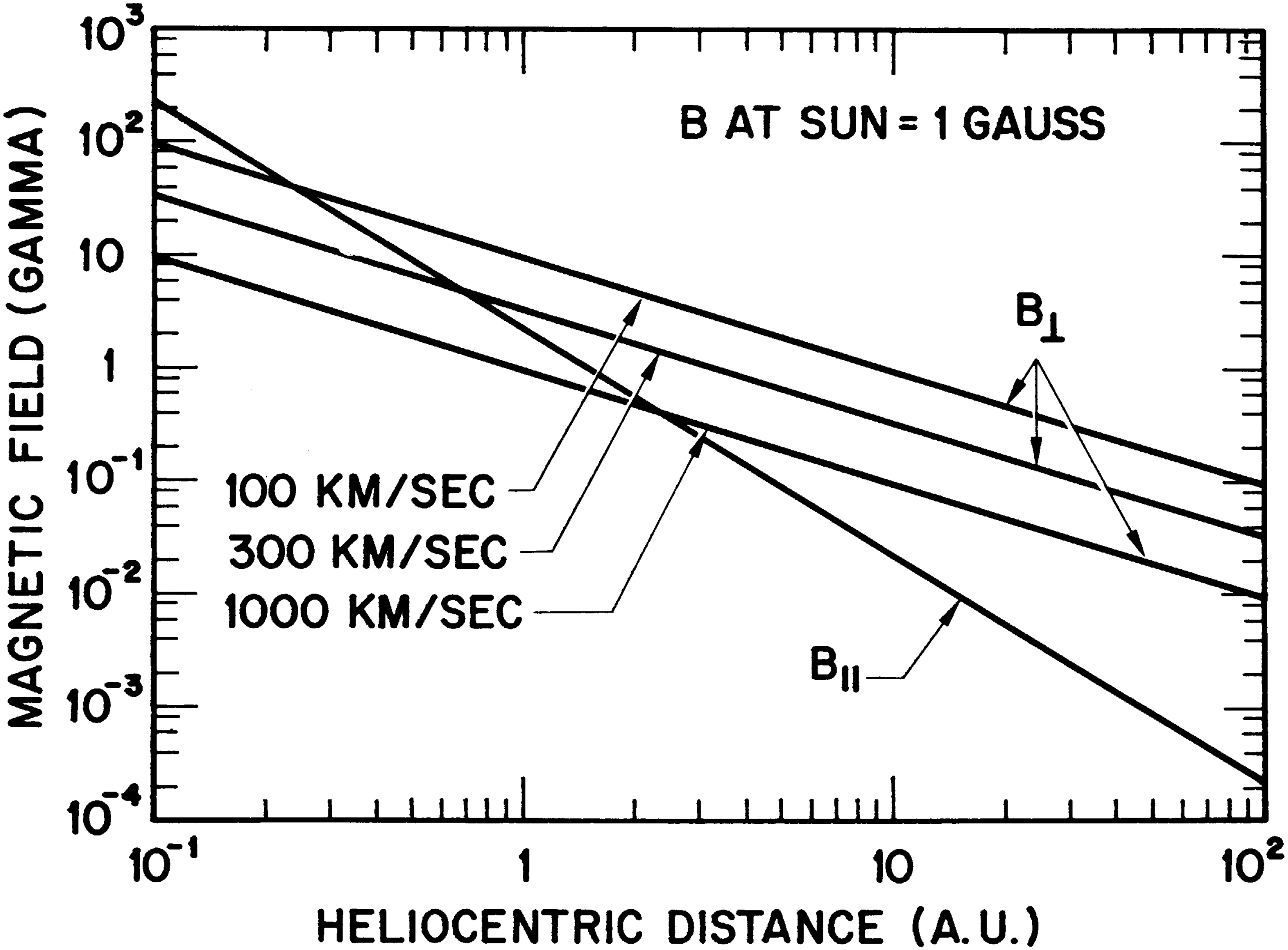
B AT SUN = 1 GAUSS
$B_{\perp}$
$B_{\parallel}$
100 KM/SEC
300 KM/SEC
1000 KM/SEC
MAGNETIC FIELD (GAMMA)
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
1
10
10^{2}
HELIOCENTRIC DISTANCE (A.U.)

Fig 1

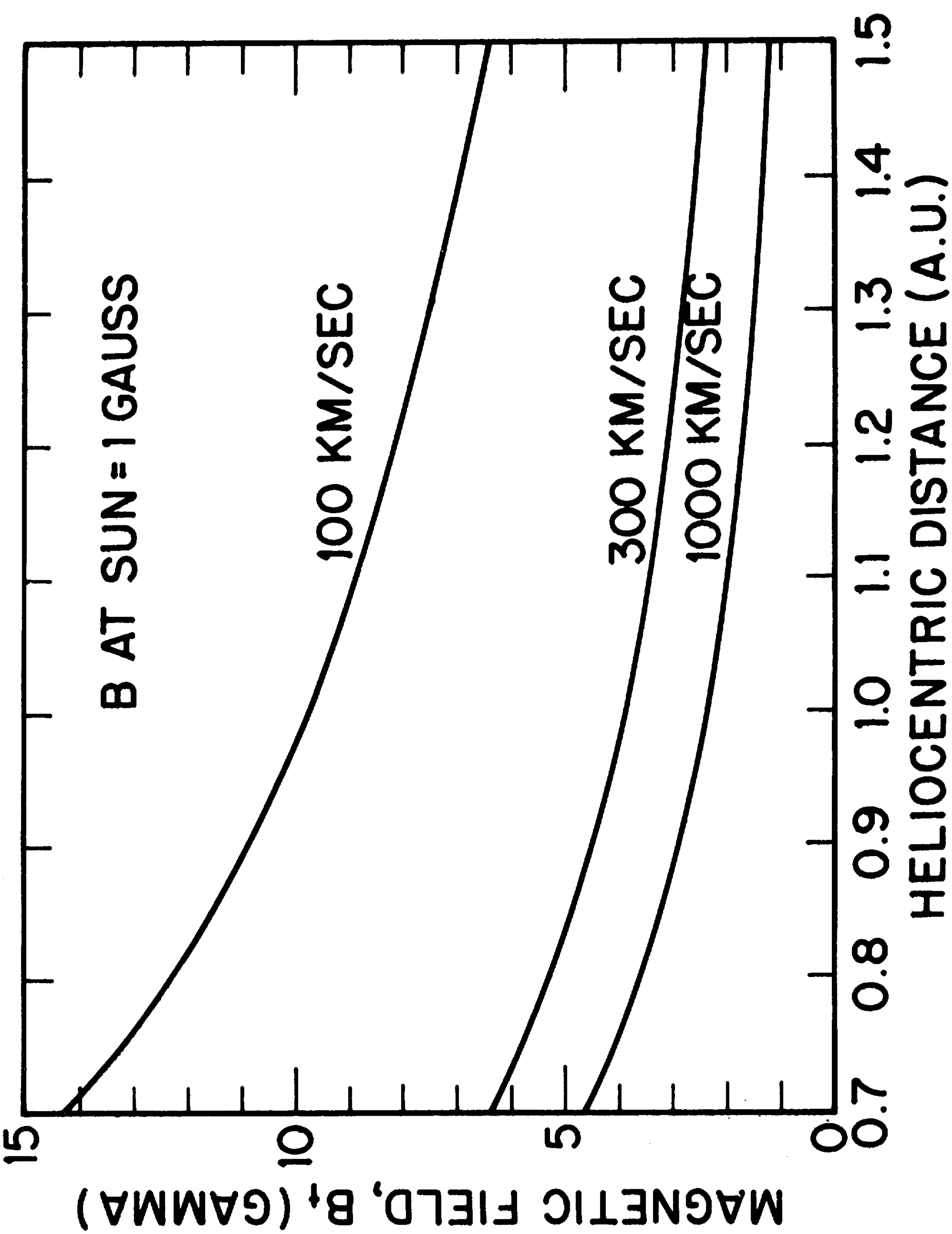
B AT SUN = 1 GAUSS
100 KM/SEC
300 KM/SEC
1000 KM/SEC
MAGNETIC FIELD, B, (GAMMA)
15
10
5
0
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
HELIOCENTRIC DISTANCE (A.U.)

Fig. 2

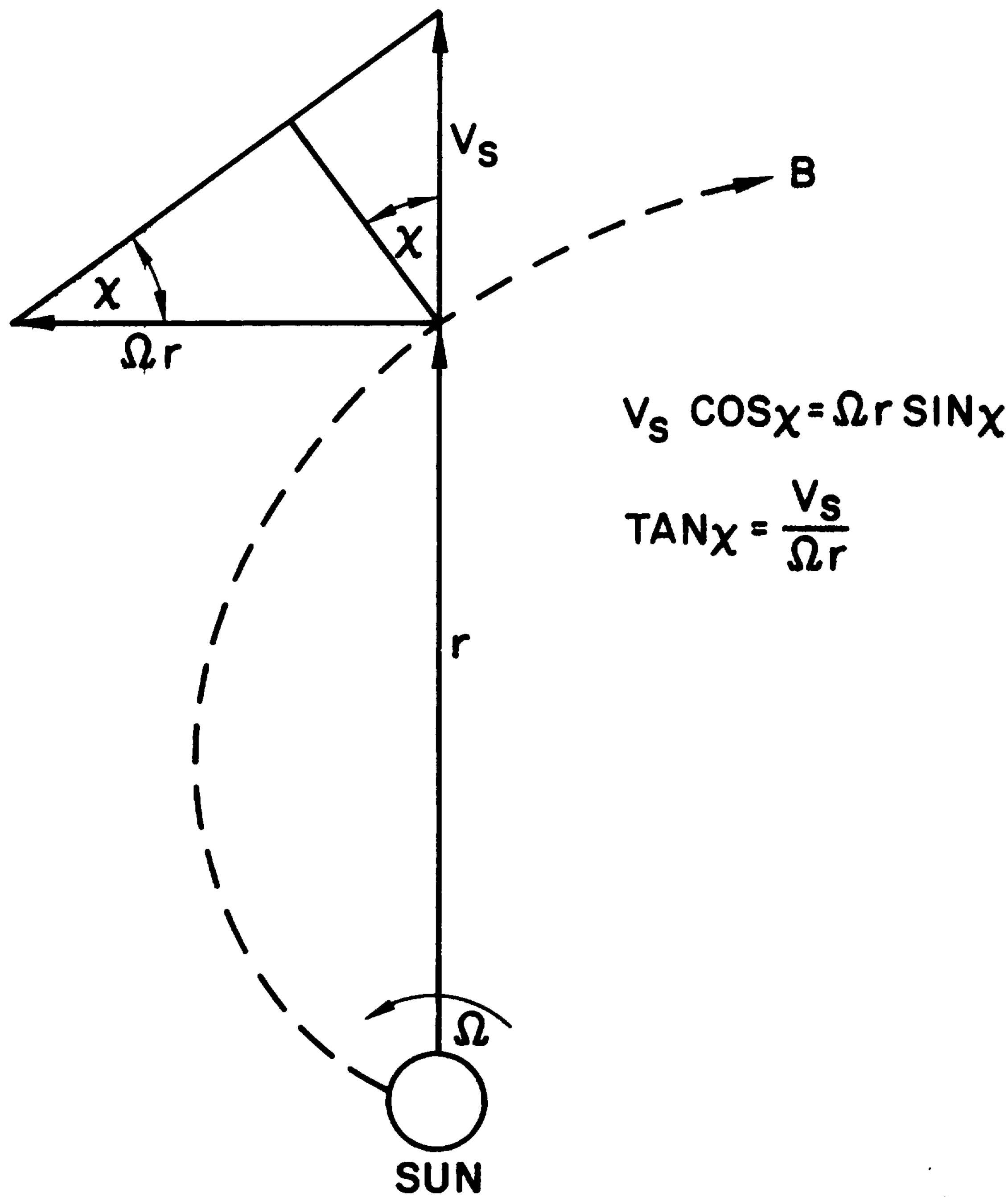
V_s
B
χ
χ
Ωr
$V_s \cos\chi = \Omega r \sin\chi$
$\tan\chi = \dfrac{V_s}{\Omega r}$
r
Ω
SUN

Fig 3

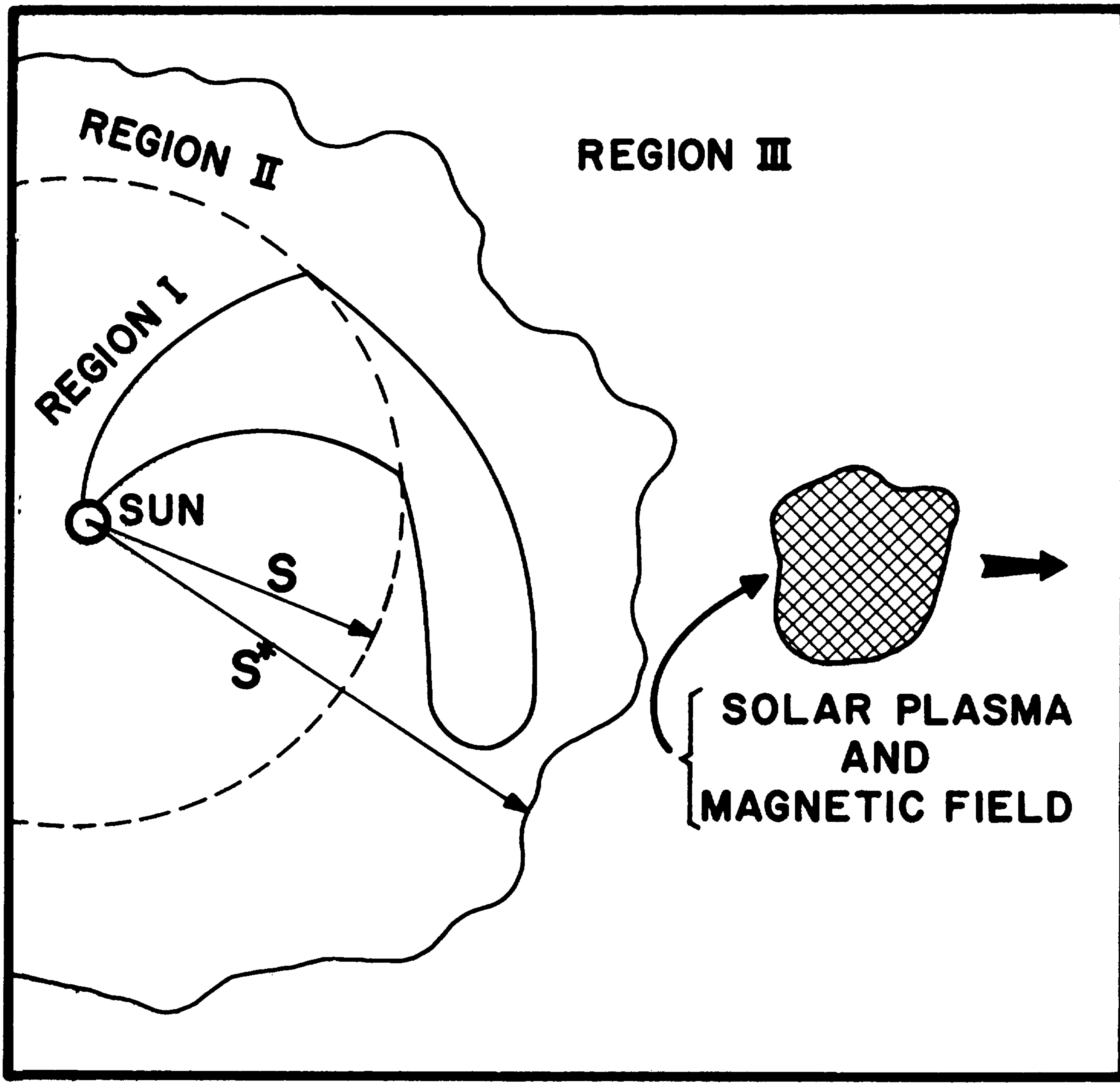
REGION II
REGION III
REGION I
SUN
S
S*
SOLAR PLASMA
AND
MAGNETIC FIELD

Fig. 4

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